Experimental Verification of a Horizontal-Refraction-Tomography Technique Using North Pacific Acoustic Laboratory Data (Continuation)

Alexander G. Voronovich
NOAA/OAR/ETL, R/ ET1, 325 Broadway, Boulder, CO 80305-3328
phone: (303)-497-6464 fax: (303)-497-3577 email: alexander.voronovich@noaa.gov

Vladimir E. Ostashev
University of Colorado/CIRES, 325 Broadway, Boulder, CO 80305-3328
phone: (303)-497-3712 fax: (303)-497-3577 email: vladimir.ostashev@noaa.gov

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LONG-TERM GOALS

1. To study a feasibility of using the horizontal refraction angles (HRA) for acoustic tomography of the ocean's inner structure.
2. To study the statistical characteristics of HRA for low-frequency, long-range sound propagation in the ocean.
3. To compare theoretical and experimental results obtained and, using these results, to explore a feasibility of acoustic remote sensing of internal gravity waves.

OBJECTIVES

To obtain short-term (hours-to-days) and long-term (weeks-to-months) dependence of HRA on time. This will be done by processing the data recorded by the five vertical line arrays (VLA) during the North Pacific Acoustic Laboratory (NPAL) experiment in 1998-1999.

To study long-term trends in the dependence of HRA on time using the data obtained during the NPAL experiment.

APPROACH

In 1998-1999, a billboard acoustic array of NPAL was installed near the coast of California and recorded broadband acoustic signals transmitted by a source located near Kauai. The transmitted signal consisted of 75 Hz carrier which was phase-modulated. The distance between the source and the array was about 4000 km. The billboard array consisted of five VLA which were positioned along the line approximately perpendicular to the acoustic path. The data obtained during the NPAL experiment are unique since acoustic signals have not been previously recorded by a billboard array. Our main goal in signal processing of the data was to study the dependence of the HRA α on time. This goal is important for understanding low-frequency, long-range sound propagation in the ocean and development of new acoustic remote sensing techniques of ocean inhomogeneities.

Two approaches were developed for signal processing of the NPAL data. The first approach is based on an assumption that the sound field incident on the billboard array is a superposition of plane waves arriving from a particular horizontal direction. This approach is called the ray-based approach. The

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second approach employs a modal representation of the sound signal incident on the billboard array. Both approaches were described in detail in our 2002 ONR report.

WORK COMPLETED

First, theoretical background for ray-based and modal-based approaches were developed. Then, computer codes for accomplishing both approaches were developed. These codes included assimilation of the coordinates of the hydrophones and their time correction provided in the NPAL database. Using these codes, we processed acoustic signals recorded during the NPAL experiment. The obtained results were analyzed. Some of these results were compared with theoretical predictions.

RESULTS

Using the ray-based approach, we obtained the dependence of HRA α on time for the period of the NPAL experiment from $t = 197$ till $t = 546$ day. (Note that 277 day corresponds to October 2, 1998.) This dependence is shown in Fig. 1, where crosses correspond to computed values of α. In the figure, each HRA α was computed together with its standard deviation σ, which were in the range from 0.13^0 to 0.6^0. The mean value of all standard deviations of HRA α shown in Fig. 1 is $\bar{\sigma} = 0.37^0$.

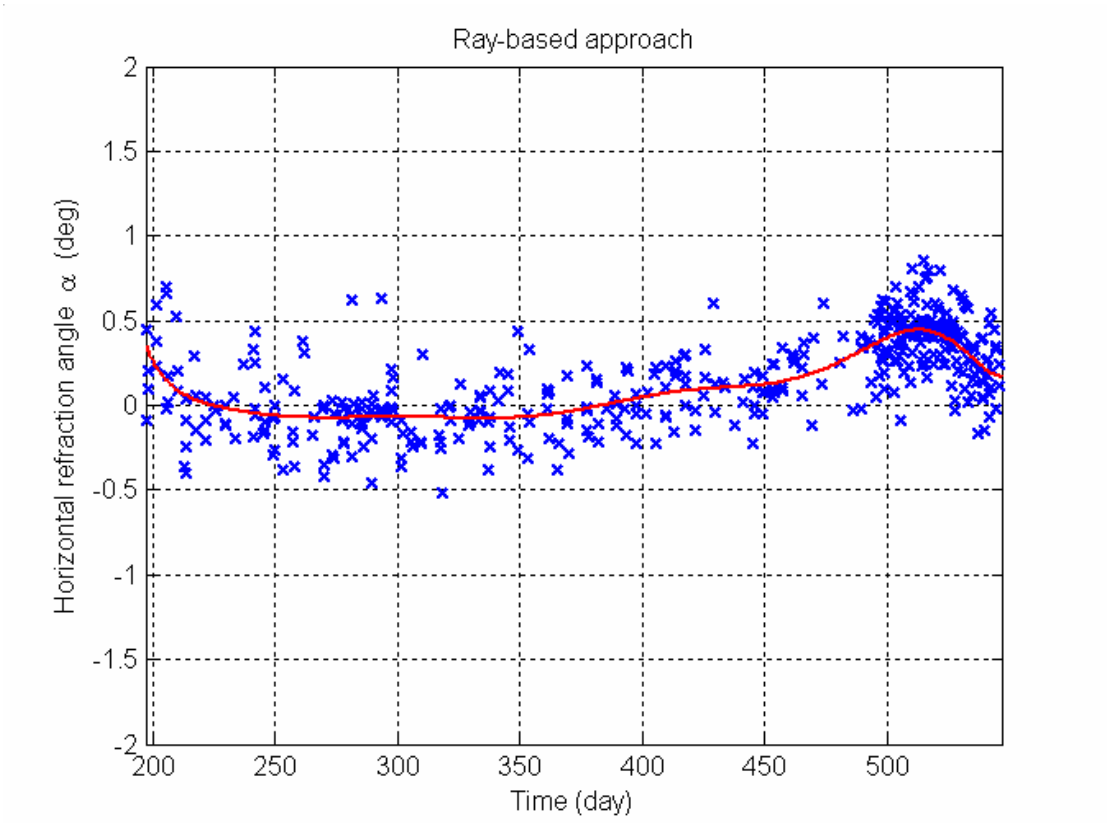

Figure 1. The dependence of HRA α on time obtained using the ray-based approach.

It is seen from Fig. 1 that short-term (hours-to-days) variations of α are of the order of $0.3 - 0.5^0$. These variations are probably due to sound scattering by internal gravity waves. Long-period (weeks-to-months) variations of HRA α are not seen in the figure. If they do exist, they are masked by short-

term variations. The solid line in Fig. 1 is the least square data fit by a polynomial of the order 10 and is interpreted as a seasonal variation of α. In the mid-spring till mid-summer of 1998 and 1999 (197-210 and 470-545 days), the value of α is positive and reaches 0.4^0. This value of α corresponds to a relative horizontal gradient of the sound speed $c^{-1}dc/dy = 3.6\times10^{-6}$ 1/km. Such a gradient of the sound speed is consistent with those measured *in situ*.

Using NPAL data, we also studied the cross-correlation coefficient between signals at different pairs of VLA versus the distance l between these VLA. The results obtained for $t = 257.2873$ day are shown in Fig. 2. The dashed line in the figure is the theoretical prediction $\exp(-l^2/r_c^2)$, where r_c is the horizontal coherence radius of the sound signal impinging on the billboard array. Figure 2 is typical for other days of the experiment. It follows from this analysis that r_c varies in the range 500-1000 m.

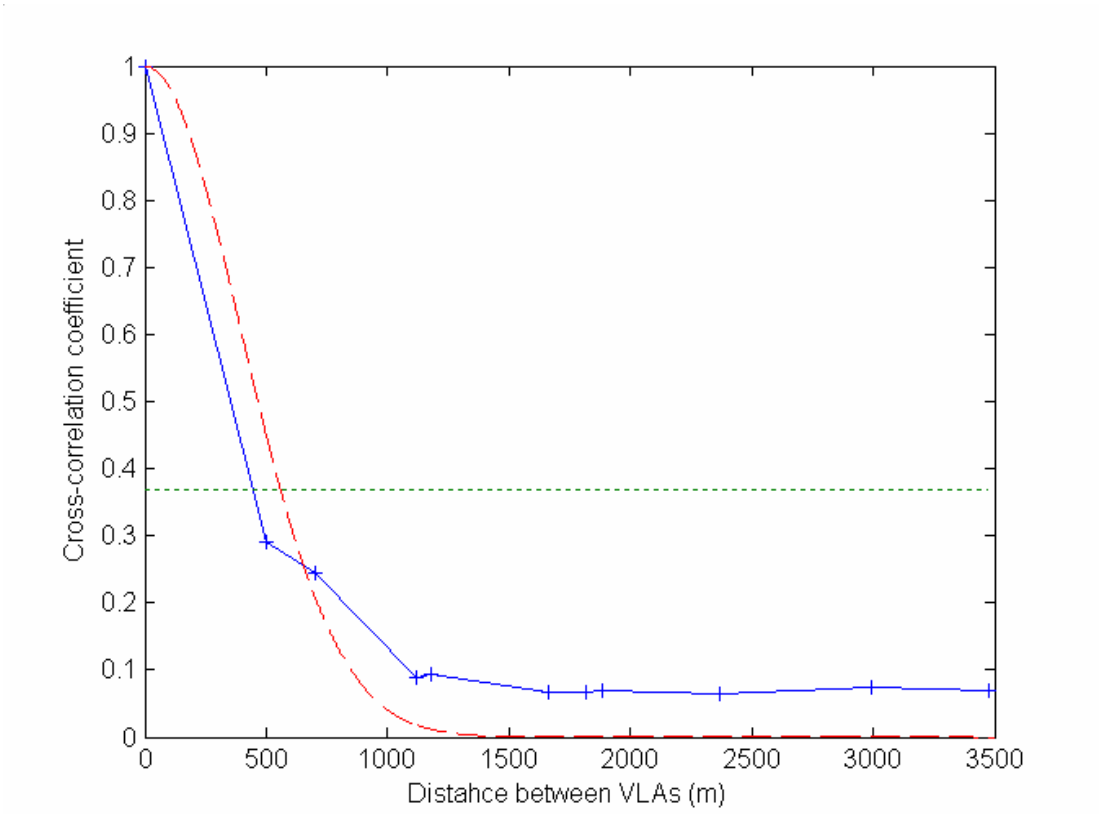

Figure 2. The cross-correlation coefficient versus the distance between VLA.

The coherence radius r_c is related to the standard deviation $\bar{\sigma}$ of angles at which the wave front is impinging on the array by the following formula: $\bar{\sigma} = \sqrt{2}/k_0 r_c$, where k_0 is a reference wavenumber. According to this formula, the standard deviation $\bar{\sigma} = 0.37^0$ corresponds to the correlation radius $r_c \approx 700$ m of the sound field impinging on the array. This estimate of r_c is in agreement with that obtained from analysis of the cross-correlation coefficients, see Fig. 2.

The modal approach in signal processing of the NPAL data was used to confirm that a seasonal trend in HRA α shown in Fig. 1 does exist. The dependence of α (shown as "+" in figure) on time obtained by this approach is plotted in Fig. 3. The solid line is the best data fit to the polynomial of the order of

10. The overall dependence of HRA α on time shown in Fig. 3 is very similar to that obtained by the ray-based approach (Fig. 1). This indicates that the seasonal trend in HRA probably does exist.

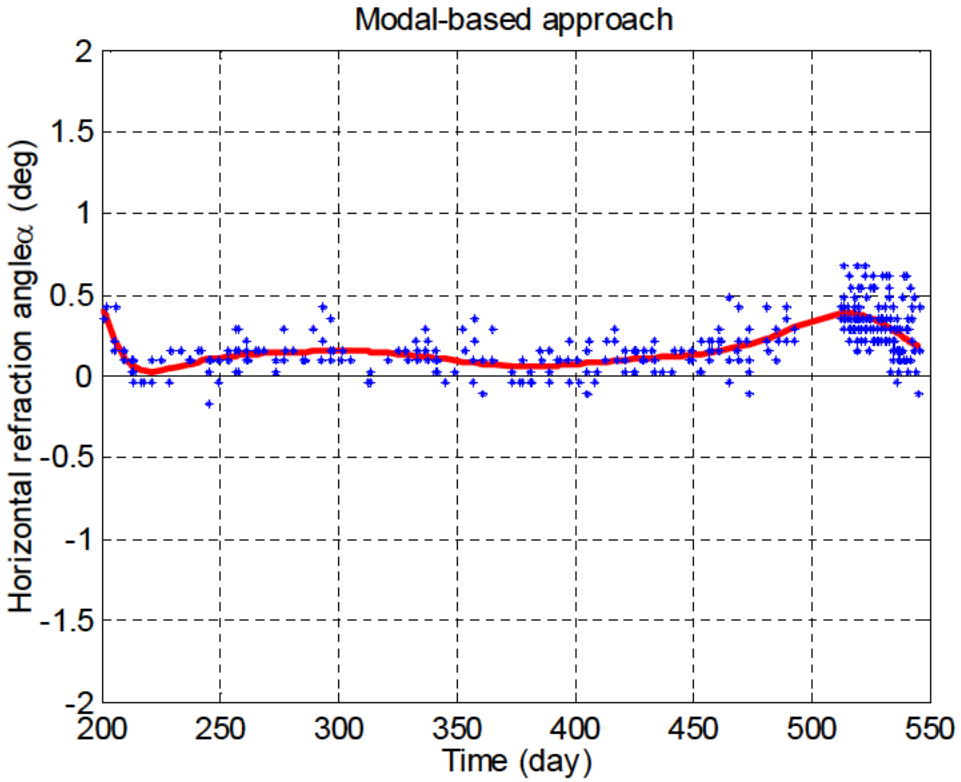

Figure 3. The dependence of HRA α on time obtained using the modal approach.

IMPACT/APPLICATIONS

Using ray-based and modal-based approaches for signal processing of the data recorded during the 1998-1999 NPAL experiment, we revealed a seasonal trend in horizontal refraction angle of sound signals propagating from Kauai to the coast of California. Thus, measurements of horizontal refraction can be used for remote sensing of ocean inhomogeneities. Appropriate acoustic experiments carried out at shorter propagation paths and in more active regions of the ocean would allow to monitor temporal variability of the horizontal inhomogeneities. This information is hardly possible to obtain by contact measurements at a reasonable cost.

TRANSITIONS

None.

RELATED PROEJCTS

The related projects are: (a) The NPAL experiment, which is briefly described above. A detailed description of the experiment is available at http://atoc.ucsd.edu/npal/billboard.
(b) Acoustic uncertainty DRI (sponsored by ONR).

PUBLICATIONS

1. A.G. Voronovich, V.E. Ostashev, and the NPAL group (J.A. Colosi, B.D. Cornuelle, B.D. Dushaw, M.A. Dzieciuch, B.M. Howe, J.A. Mercer, R.C. Spindel, and P.F. Worcester), "Experimental investigation of the horizontal refraction of acoustic signals in the ocean", *Izvestiya, Atmospheric and Oceanic Physics*, **38**, No 6, 716-719 (2002).

2. A.G. Voronovich, V.E. Ostashev, and the NPAL Group (J.A. Colosi, B.D. Cornuelle, B.D. Dushaw, M.A. Dzieciuch, B.M. Howe, J.A. Mercer, R.C. Spindel, and P.F. Worcester), "Studies of horizontal refraction of acoustic signals recorded by NPAL", in Proceedings of the 9th L.M. Brekhovskikh's conference "Ocean Acoustics", 88-91, Moscow (2002).

3. A.G. Voronovich, V.E. Ostashev, and the NPAL Group (J.A. Colosi, B.D. Cornuelle, B.D. Dushaw, M.A. Dzieciuch, B.M. Howe, J.A. Mercer, R.C. Spindel, and P.F. Worcester), "Horizontal refraction of acoustic signals propagating over a long-range in the ocean", in Proceedings of Acoust. Soc. Am. Meeting, Cancun, Mexico (2002).

4. A.G. Voronovich, V.E. Ostashev, and The NPAL group (J.A. Colosi, B.D. Cornuelle, B.D. Dushaw, M.A. Dzieciuch, B.M. Howe, J.A. Mercer, R.C. Spindel, and P.F. Worcester), "Studies of horizontal refraction and scattering of low-frequency acoustic signals using a modal approach in signal processing of NPAL data", *J. Acoust. Soc. Am.*, **113**, No 4, Pt. 2, 2333 (2003).

5. A.G. Voronovich, V.E. Ostashev, and the NPAL Group (J.A. Colosi, B.D. Cornuelle, B.D. Dushaw, M.A. Dzieciuch, B.M. Howe, J.A. Mercer, R.C. Spindel, and P.F. Worcester), "Horizontal refraction and coherence of acoustic signals propagating over a long-range in the ocean" , *J. Acoust. Soc. Am.* **112**, No 5, 2232 (2002).

PATENTS

None.

HONORS/AWARDS/PRIZES

None.